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LIQUID JET BREAKUP AND ATOMIZATION IN ROCKET CHAMBERS UNDER DENSE SPRAY CONDITIONS

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I. Research Objectives and Potential Impact on Propulsion

One of the most important issues in liquid rocket propulsion is how to promote the mixing of liquid propellants and eliminate the problem of combustion instability due to inadequate spays in thrust chambers. To address this issue, it is necessary to seek a good understanding of important mechanisms controlling the liquid jet breakup and atomization processes in the dense spray region. Owing to the complexity of the phenomena and the difficulty in obtaining experimental measurements, previous studies of spray combustion have focused largely on the dilute region, as identified in the 1988 Workshop on "Mixing and Demixing Processes in Multiphase Flows with Applications to Propulsion Systems," sponsored by the University Space Research Association of NASA Marshall Space Flight Center and the 1989 JANNAF Workshop coordinated by Chiu and Gross. Very little work has been conducted to explore the characteristics of dense spray, including the behavior of the jet boundary surface, core breakup length, liquid jet ligament size, local void fraction, and velocity distribution. In the absence of these data, it is impossible to realistically predict the rates of mixing of liquid propellants and thus engine performance.

To fill the above technological gaps and to extend the state-of-the-art in spray combustion, the present research project was initiated in September 1988 to study the phenomena of dense spray. Two advanced diagnostic techniques have been established and employed in the project. The first technique involves the use of a real-time X-ray radiography system along with a high-speed CCD Xybion camera and an advanced digital image processor to investigate the breakup processes of the liquid core. The focus of this part of the project is to determine the inner structure of the liquid jet and to correlate the core breakup length and local void fraction to various controlling parameters such as the characteristic Reynolds and Weber numbers. The second technique involves the use of a high-power copper-vapor laser to illuminate the liquid jet via thin sheets of laser light, with the scattered light being photographed by a Xybion electronic camera synchronized to the laser pulse. This technique, which is capable of recording the breakup event occurring within 25 nano-seconds, enables us to freeze the motions of the jet and liquid droplets. The focus of this part of the project is to determine the outer structure of the liquid jet and to discover the configuration of the surface waves, the spray pattern, and the droplet size distribution in the non-dilute region. Results obtained by these two advanced diagnostic techniques will provide the much needed database for model development and accurate prediction of engine performance. The present work also represents a breakthrough in the area of advanced diagnostics of dense sprays.

II. Current Status and Results

To overcome the difficulty in experimental measurements in the dense spray region, the aforementioned advanced diagnostic techniques (i.e., the real-time X-ray radiography and the laser-illuminated flash-photography techniques) have been established and employed in the project. A liquid injection system was designed and fabricated for this purpose. The injector consists of a single coaxial element of inner jet diameter and annular area similar to that of a single SSME injector element. The injector used in this project is of modular design so that the inner jet diameter and annular gap dimensions can be easily varied by exchanging appropriate components. The fluid supply and recovery system was assembled in conjunction with the X-ray radiography system, and a number of real-time radiography tests was performed to calibrate the test procedure and working fluid.

Several flash-photographic tests of coaxial jets at various conditions were conducted using light-pulse illumination with a pulse duration of ~10 μs. Unfortunately, this pulse duration was found to be too long to completely freeze the liquid droplet/ligament motions for all but the lowest injected gas-to-liquid velocity ratios. Nevertheless, the series of photographs did provide useful qualitative information on the physical mechanisms governing the liquid jet breakup due to the coaxial gas flow. To upgrade the flash-photography technique, a copper-vapor laser and a CCD Xybion electronic camera were obtained recently. The laser, with a pulse duration of ~30 ns, and the camera, with a gated exposure time ranging from 25 ns to 50 ms, can be synchronized to produce a video tape of the jet breakup event consisting of a series of completely-frozen-motion pictures. The laser beam delivery system and the optical setup for laser sheet generation are currently under construction.

Several real-time X-ray radiography tests of coaxial jets have been successfully conducted using nitrogen gas and an X-ray absorbing aqueous solution of potassium iodide as the working fluids. The mass flow rates of liquid and gas have been calibrated, and were recorded for each test to determine the relative velocity used to form the characteristic Reynolds and Weber numbers for qualitative analysis of data. A typical run involves passing a continuous stream of X-rays through a section of the near-injector region of the coaxial jet. Where the liquid fraction is highest, the greatest amount of X-ray attentuation occurs. The X-rays that reach the screen of the image intensifier are converted to light photons, and an optical signal is received by the Xybion electronic camera. The output from the camera is in RS-170 video format consisting of 30 controlled-exposure pictures per second, each picture having an exposure time as short as 25 ns. The video signal is then recorded on tape and analyzed using the Quantex 9210 digital image processor to determine the liquid jet inner structure, core breakup length, and local void fraction for each frame of the video sequence.

A typical set of results for coaxial jets obtained from the image analysis of the real-time X-ray radiography tests is depicted in Figures 1 and 2. Figure 1a shows a single frame from the video sequence of a coaxial jet after an analysis procedure that equalizes the X-ray image in the selected area. In this procedure, the regions of highest liquid fraction in the area are assigned a radiance level of zero, and the highest void regions assigned a radiance level of 255. This spreads out the gray scale across the area of interest for more pronounced distinction of the image, thus greatly enhancing direct visualization of the jet. Figures 1b to 1d show the radiance level distributions across the jet in both vertical (i.e., transverse) and horizontal (i.e., streamwise) directions. Figure 1b is a vertical profile across the jet taken at an upstream location where there is still a well-defined liquid core. On the other hand, Fig. 1c is a vertical profile taken at a location downstream of the core breakup length. At this location, the liquid core is no longer intact as voids are evident within the core region. Figure 1d is a horizontal profile along the jet centerline. The large void in the core depicted by the spike in the radiance profile clearly indicates that the core is no longer intact. Figure 1e is an example of the isophote analysis in which regions falling into a selected range of radiance levels are shaded. In this figure, the darkest region includes the liquid ligaments and large droplets, whereas the shaded region represents the intact liquid core. Based on this isophote result, the core breakup length for this low-pressure test (@ 1 atm) was determined to be about 5-3/4 inches from the injector. A similar isophote picture for a coaxial jet at higher gas-to-liquid relative velocity is shown in Fig. 1f, where the core breakup length was found to be about 3-1/4 inches. The decrease in the breakup length is evidently due to an increase in the characteristic Reynolds number. Figures 2a and 2b demonstrate the capability of the image processor to assign color values to the different shades of gray, allowing human eyes to better distinguish the existence of various regions. Figure 2a is from the test case of that depicted in Fig. 1e whereas Fig. 2b corresponds to Fig. 1f. Note the difference in core breakup length for the two cases, where the continuous blue color region represents the intact liquid core. Finally, Figs. 2c and 2d show another image analysis feature (i.e., the "zoom") that magnifies the X-ray image, allowing a close-up observation of the details of the liquid core and ligament formation region. Quantitative analysis of the data is now underway.

The above X-ray results represent a set of benchmark data for liquid jet breakup in the dense spray region that has not been observed heretofore. These data, together with those to be obtained in the coming year, will provide a much needed database for the development and validation of liquid-rocket-engine performance models.

III. Proposed Work for Coming Year

The X-ray radiography study of coaxial jet breakup in the non-dilute region under open-atmosphere conditions will be completed in the very near future. More results similar to those shown in Section II will be obtained so that the liquid core breakup length can be correlated to the characteristic Reynolds and Weber numbers as well as other pertinent parameters such as the injector flow area ratio (i.e., ratio of the annular gas flow area to liquid flow area). With the modular design of the injector, this area ratio can be easily varied. To complete the liquid jet breakup study for the case of injection into atmospheric pressure, the laser-assisted flash-photography technique will also be used to produce stop-action video pictures of the coaxial jets with very short exposure times (~25 ns). A data correlation for the surface breakup phenomena in the non-dilute region will be performed.

In addition to the above work items, much of the effort in the coming year will be devoted to studying the breakup processes of a coaxial flow injected into a high-pressure chamber in order to simulate more closely the liquid rocket engine environment. An existing high-pressure, windowed test chamber will be modified for this purpose. The chamber has a large flow area for the spray to develop with full length windows available for the lower pressure tests (<100 psig). Smaller windows will be fabricated for tests up to about 1,000 psig pressure. The pressure in the chamber, to be monitored with a pressure transducer, will be held constant during the tests by the use of a back-pressure regulator. A bursting diaphragm will be included as a safety precaution in case of overpressurization. Also, a liquid collection reservoir will be added so that the liquid will not fill up the test area. This reservoir may serve as a surge tank as well. The pressurized windowed test chamber will be employed for both real-time X-ray radiography and laser-assisted flash-photography studies. In the former case, the image processing technique will be used whereas in the latter case, a secondary window will be machined at the top of the chamber to direct the laser sheet into the test chamber in order to illuminate the jet. Video data analogous to those obtained in the open atmosphere tests will be acquired for various chamber pressures. The correlations deduced from the one atmosphere data will be modified and extended to include the effect of variations in chamber pressure. Additional open-atmosphere and high-pressure tests will be performed to further confirm the validity of the correlations. Results including the effect of elevated chamber pressures will be obtained, which can be directly applicable to liquid rocket engines. They will provide a useful guideline for modeling the jet breakup processes as well as serve as an empirical input into engine performance models. A detailed itemized work statement for the coming year is given below.

1. Complete the X-ray radiography study of coaxial jet breakup under open-atmosphere conditions.

2. Correlate liquid core breakup length based on the open-atmosphere data.

3. Conduct laser-assisted flash-photography tests under open-atmosphere conditions.

4. Modify the existing windowed test chamber for high-pressure studies.

5. Calibrate flow conditions inside the pressurized chamber at different operating conditions.

6. Conduct X-ray radiography jet-breakup tests in the pressurized chamber.

7. Conduct laser-assisted flash photography tests in the pressurized chamber.

8. Extend the open-atmosphere correlations to include elevated pressure effect.

9. Perform additional open-atmosphere and high-pressure tests to further confirm the validity of the correlations.

10. Initiate model formulation of the two-phase coaxial jet breakup processes.

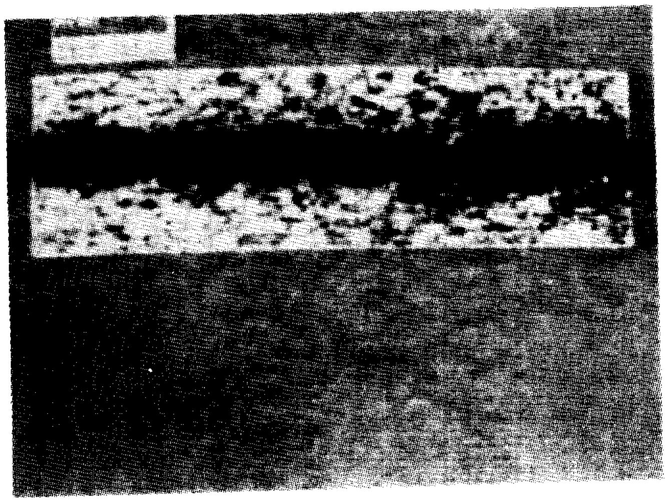

Figure 1a. X-ray image of coaxial jet after equalization (contrast stretching). Figures 1b-1e are derived from this image.

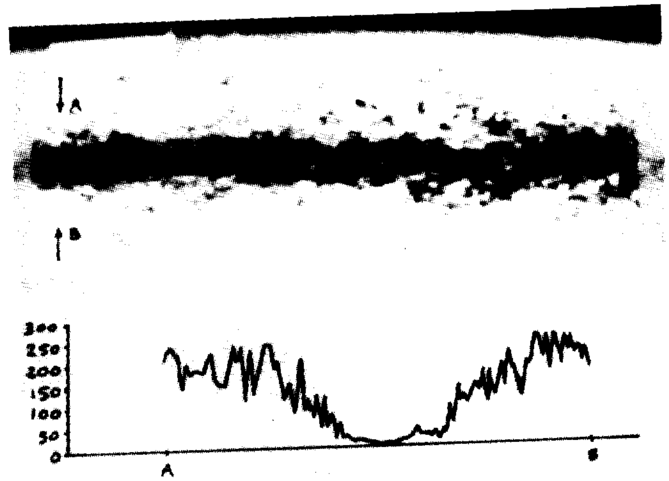

Figure 1b. Profile of radiance level versus vertical position across the jet at a location approximately 2½ inches downstream of the injector. Arrows indicate location where profile was taken. Profile indicates well-defined liquid core.

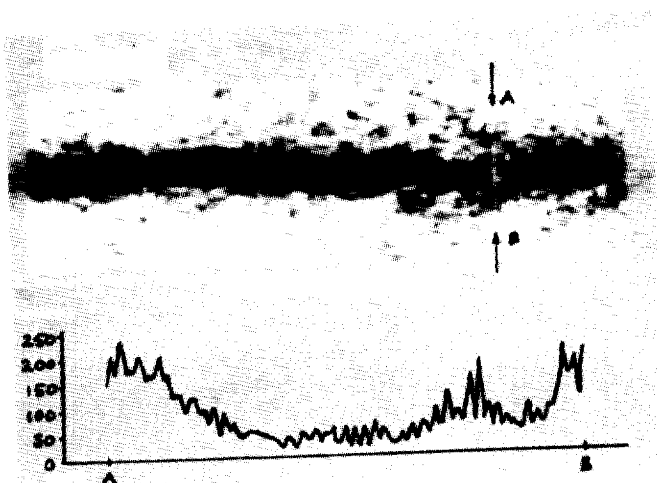

Figure 1c. Profile of radiance level versus vertical position across the jet at a location downstream of the liquid core breakup length. Arrows indicate location where profile was taken.

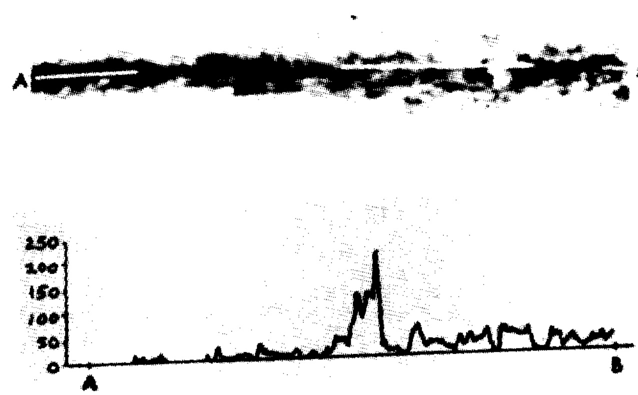

Figure 1d. Profile of radiance level versus horizontal position along the jet centerline. The spike in the radiance profile indicates that the liquid core is no longer intact at that location.

Figure 1e. Isophote analysis for coaxial jet. Same jet as depicted in Figures 1a-1d. Core breakup length is indicated at about 5 3/4 inches from the injector (1 atm test).

Figure 1f. Isophote analysis for a coaxial jet of higher injected gas-to-liquid relative velocity (1 atm test). Note the decrease in indicated core breakup length to 3¼ inches from the injector.